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Demonstration of an Improved Subfilter Stress Closure for WRF

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1. INTRODUCTION

A new suite of models for representing subfilter-scale (SFS) turbulence stresses has been implemented into the Weather Research and Forecasting (WRF) model for improved large eddy simulation (LES) capability. Our Dynamic Reconstruction SFS stress model (DRM) is based upon reconstruction of the resolvable subfilter-scale (RSFS) stresses combined with separate subgrid-scale (SGS) eddy viscosity models. DRM includes a module for reconstructing the RSFS stresses, a dynamic subgrid eddy viscosity (SGS) model and a near-wall stress model (following Chow et al, 2005).

The DRM SFS models are physically based, permit backscatter of energy, and do not assume a local balance between turbulence production and dissipation (as many SFS models do). As such, our models are well suited to simulating flow over complex terrain, including urban environments, where turbulence production and dissipation are frequently not in local balance.

We present a brief overview of the approach as well as results from simulations in WRF of flow over both a rough flat plate and an isolated two-dimensional hill.

2. BASIS OF THE DRM SFS MODEL

The large eddy simulation technique is based on application of a low-pass filter to the flow field equations. This filter separates the fields into a resolved component that is advanced using the filtered governing equations and a subfilter component that is parameterized in a SFS model.

As presently constituted WRF contains no explicit low-pass filter, hence the grid implicitly provides the filtering that separates the fields into resolved and subgrid components. The effects of all unresolved motions on the resolved-scale fields are modeled as one piece using one of WRF's two SGS eddy-viscosity models.

Our DRM model is instead based on velocity partitioning, also known as "explicit filtering with reconstruction" (Gullbrand and Chow, 2003). We apply a smooth, explicit (tophat) filter with a width twice that of the grid to the flow field variables both to separate those into resolved and subfilter components and to reduce errors arising from finite difference operators and aliasing. The application of an explicit filter that is wider than the grid separates the unresolved portion of the field into two subregions, one containing motions that are smaller than the grid (subgrid) and another that exists between the grid and the filter (see Figure 1). The motions contained in the latter category are, in principle, resolvable on the grid, and are therefore denoted as resolvable subfilter-scales (RSFS). The RSFS motions are modeled separately from the subgrid scales using a velocity reconstruction approach. This approach utilizes the explicit filter to construct a series expansion of the RSFS fields (Stoltz and Adams, 1999) which is then filtered again to compute the RSFS portion of the SFS stress. The RSFS stresses are then added to the SGS stresses that are computed in separate SGS eddy-viscosity models

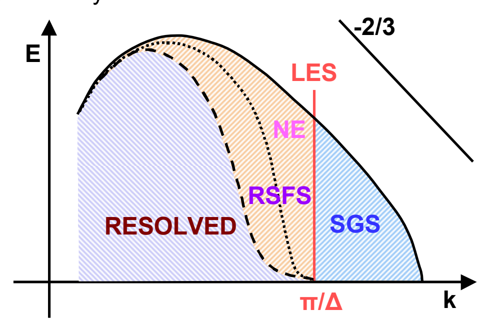

Figure 1: Idealized partitioning of spectral energy during LES. The solid line depicts the full energy spectrum one would obtain using a spectral LES—one that smoothly separates the flow into resolved and SGS components. Discrete solvers introduce errors and attenuate energies of scales greater than π/Δ. Explicit filtering (dashed line) improves representation of the resolved-scale component by damping errors and allowing for reconstruction of the RSFS component (up to the limit of numerical errors arising from the discrete solver (NE, dotted line)) (adapted from Chow et al, 2005).

While the RSFS component of the SFS stress can (and should) be included in any discrete SFS model, deficiencies in the SGS model will limit the effectiveness of the combined SGS/RSFS approach. To circumvent the errors introduced by WRF's native SGS models (a TKE-based and a static Smagorinsky closure) we implemented an improved SGS model, the dynamic model of Wong

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and Lilly (1994). This model determines the so-called Smagorinsky constant as a function of time and space using the RSFS stresses computed on both the explicit mesh and a test mesh of width 2Δ using the least squares approach of Lilly, 1992. The model eddy diffusivity coefficients are test-filtered twice and negative values are clipped at a value of -1.5e-5. This stabilizes the approach while also allowing for local backscatter effects. An additional near-surface stress is added for z < 4Δ to account for unresolved eddies near the surface.

3. RESULTS

The DRM model was tested against WRF's native SGS models using idealized simulations of neutral flow over two rough surfaces, a flat plate and a two-dimensional hill. Each simulation was integrated using a constant, uniform geostrophic wind of 10 m/s in the zonal direction and a surface stress given by the log law using a roughness of 0.1m. The simulations were conducted using a domain of 1312m in each horizontal direction and a height of 1500m with 42 gridpoints in each direction. The mesh spacing was 32m in each horizontal direction while the vertical grid was stretched from ~5m near the surface to ~50m at the domain top.

3.1 Flow over a flat, rough plate

Flow over a flat, rough plate affords comparison to the theoretical solution, the logarithmic wind speed profile (log law) in the neutral surface layer. Figure 2 shows the (dimensionless) vertical distributions of wind speed (on the ordinate) versus normalized height (on the abscissa) using each of WRF's SFS models, the DRM model and the log law. The profiles were averaged at 20-minute intervals for 24 hours after 24 hours of spinup to achieve statistical equilibrium. Figure 2 clearly demonstrates superior agreement of the DRM with the log law.

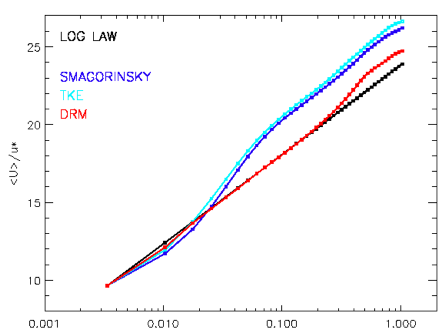

Figure 2: Dimensionless wind speed versus normalized height for flat plate simulations.

Shown in figure 3 are horizontal cross-sections of zonal velocity at ~50m using the TKE (top) and Smagorinsky (middle) SGS and the DRM (bottom) closures. Noteworthy are the reductions in streakiness in the alongstream flow direction as well as increased small-scale variability afforded by the DRM model. The reduction in streakiness coupled with the superior reproduction of small-scale detail demonstrates enhancement of WRF's applicability to LES of scenarios where smaller eddies dominate, such as stable stratification, complex terrain and urban environments.

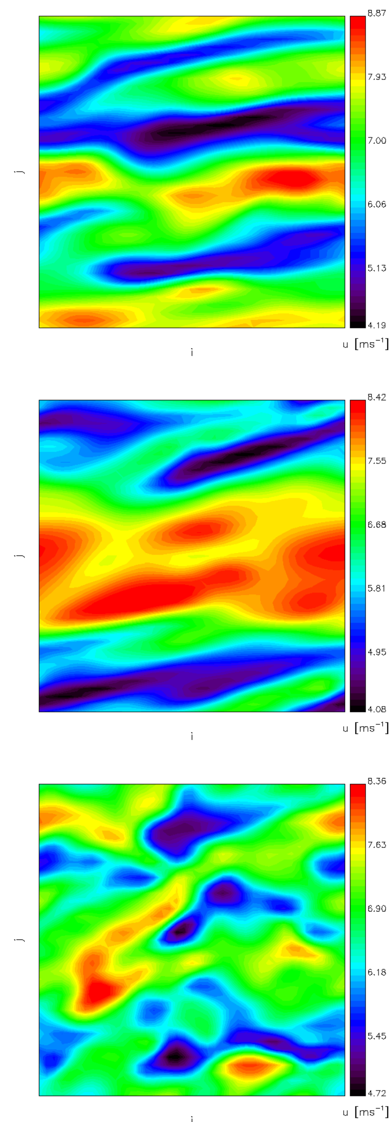

Figure 3: Horizontal cross sections of u velocity at ~50m for flat plate simulations using TKE (top), Smagorinsky (middle) and DRM (bottom) turbulence closures.

The results of the flat plate simulations demonstrate the superior performance of the DRM model over the existing WRF SFS closures. While this test case is highly idealized, it establishes a legitimate verification of the approach, and a basis upon which further complexity can be introduced and the effects more straightforwardly interpreted.

3.2 Flow over a 2-D hill

The implementation of the DRM over surface terrain was validated using simulations of flow over a symmetric 2-D hill. The 2-D hill simulations used the same parameters as the flat plate simulations except for the introduction of a Gaussian hill with sloping terrain in the x-direction and constant height in the y-direction. These simulations were run for only three hours, hence the flow had not yet equilibrated to a statistically steady state. However several significant differences between the DRM and the two native WRF SGS models are already clearly identifiable.

Figure 4 shows the geometry of the surface terrain (note the compressed vertical axis which makes the hill appear taller and steeper than it is) as well as the existence of well-defined eddy structures in the lee of the hill. These and similar features indicating the existence of recirculation vortices, are observed regularly throughout the latter two hours of the simulations using the DRM. Each of the native WRF SGS models, in contrast, produce comparatively much weaker, shallower and more intermittent recirculation patterns (not shown).

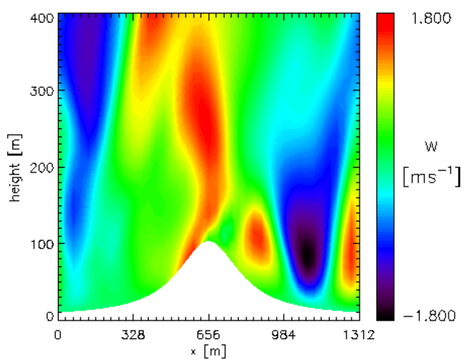

Figure 4: Contours of w-velocity in the x-z plane showing both the terrain geometry as well as the well-defined vortices in the lee of the hill produced by the DRM.

Figure 5 shows cross-sections of the u-velocity in the horizontal plane using the TKE (top), Smagorinsky (middle) and DRM (bottom) closures at ~25m. As with the flat plate simulation, each of the native WRF SGS models again results in the prediction of elongated streaks in the alongstream direction that are not replicated by the DRM. In addition, while the native WRF schemes produce minimal negative velocities indicative of recirculation in the lee of the hill, the DRM produces several regions of strong reverse flow (note the different contour levels). The reduction in alongstream streakiness as well as the enhanced reverse flow shows that, as with the flat plate, the DRM significantly improves the simulation of turbulent flow over terrain features, thereby extending WRF's LES capabilities to a variety of real-world applications involving complex terrain.

4. CONCLUSIONS

The simulations described herein demonstrate the implementation of an improved SFS model for use in large eddy simulations with WRF. While these simulations are admittedly quite idealized, they provide a framework for careful validation of the implementation as well as a straightforward basis for the interpretation of the resulting differences in the absence of complicating factors. The improvements obtained from the DRM in these idealized settings justify confidence that similar improvements will emerge from future validation experiments using more complicated real-world atmospheric forcing and surface terrain.

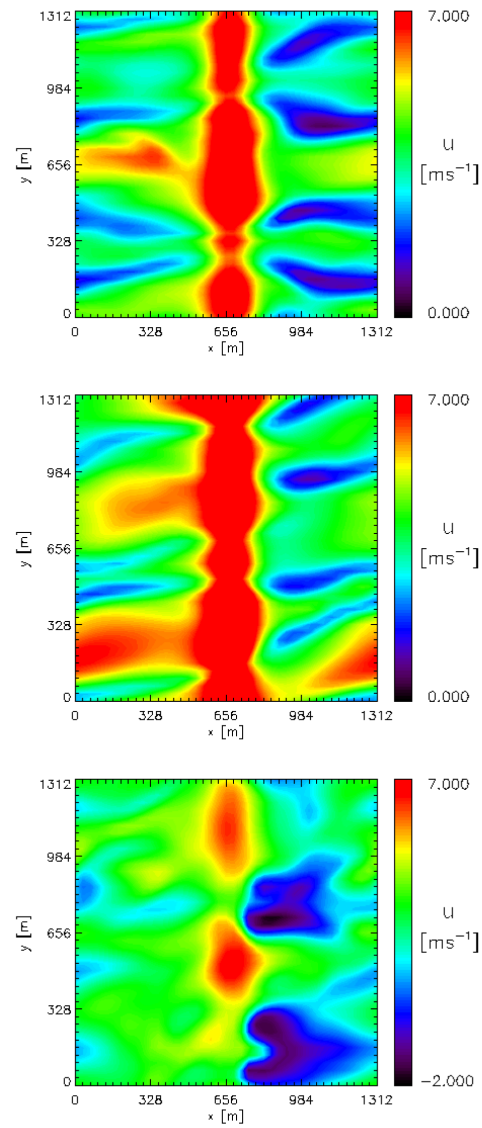

Figure 5: Contours of u-velocity at ~25m using the TKE (top), Smagorinsky (middle) and DRM (bottom) closures during simulations of flow over a 2-D hill.

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